

Double beta decay experiments: past and present achievements

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Abstract. A brief history of double beta decay experiments is presented. The best currently running experiments (NEMO-3 and CUORICINO) and their latest results are described. The best measurements and limits for the $2\nu\beta\beta$, $0\nu\beta\beta$ and $0\nu\chi^0\beta\beta$ are summarized.

1. Historical introduction

1.1. Theory

The double beta decay problem arose practically immediately after the appearance of W. Pauli's neutrino hypothesis in 1930 and the development of β -decay theory by E. Fermi in 1933. In 1935 M. Goeppert-Mayer identified for the first time the possibility of two neutrino double beta decay, in which there is a transformation of an (A, Z) nucleus to an $(A, Z+2)$ nucleus that is accompanied by the emission of two electrons and two anti-neutrinos [1]:

$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu} \quad (1)$$

It was demonstrated theoretically by E. Majorana in 1937 [2] that if one allows the existence of only one type of neutrino, which has no antiparticle (i.e. $\nu \equiv \bar{\nu}$), then the conclusions of β -decay theory are not changed. In this case one deals with a Majorana neutrino. In 1939 B. Farry introduced a scheme of neutrinoless double beta decay through the virtual state of intermediate nuclei [3]:

$$(A, Z) \rightarrow (A, Z+2) + 2e^- \quad (2)$$

In 1981 a new type of neutrinoless decay with Majoron emission was introduced [4]:

$$(A, Z) \rightarrow (A, Z+2) + 2e^- + \chi^0 \quad (3)$$

1.2. Experiment

The first experiment to search for 2β -decay was done in 1948 using Geiger counters. In this experiment a half-life limit for ^{124}Sn was established, $T_{1/2} > 3 \cdot 10^{15}$ y [5]. During the period 1948 to 1965 ~ 20 experiments were carried out with a sensitivity to the half-life on the level $\sim 10^{16} - 10^{19}$ y (see reviews [6, 7]). The 2β -decay was thought to have been "discovered" a few times, but each time it was not confirmed by new (more sensitive) measurements. The

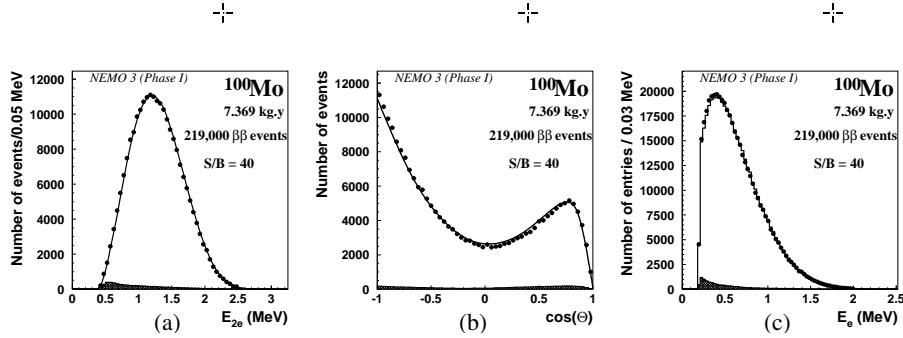


Figure 1. (a) Energy sum spectrum of the two electrons, (b) angular distribution of the two electrons and (c) single energy spectrum of the electrons, after background subtraction from ^{100}Mo with 7.369 kg.years exposure [22].

exception was the geochemical experiment in 1950 where two neutrino double beta decay of ^{130}Te was really detected [8].

At the end of the 1960s and beginning of 1970s significant progress in the sensitivity of double beta decay experiments was realized. E. Fiorini et al. carried out experiments with Ge(Li) detectors and established a limit on neutrinoless double beta decay of ^{76}Ge , $T_{1/2} > 5 \cdot 10^{21}$ y [9]. Experiments with ^{48}Ca and ^{82}Se using streamer chamber with a magnetic field and plastic scintillators were done by C. Wu's group and led to impressive limits of $2 \cdot 10^{21}$ y [10] and $3.1 \cdot 10^{21}$ y [11] respectively. During these years many sensitive geochemical experiments were done and $2\nu\beta\beta$ decay of ^{130}Te , ^{128}Te and ^{82}Se were detected (see reviews [12, 7, 13]).

The important achievements in the 1980s were connected with the first evidence of two neutrino double beta decay in direct counting experiments. This was done by M. Moe's group for ^{82}Se using a TPC [14]. There was also the first use of semiconductor detectors made of enriched Ge in the ITEP-ErPI experiment [15].

During the 1990s the two neutrino decay process was detected in many experiments for different nuclei (see [16, 17]), two neutrino decay to an excited state of the daughter nuclei was also detected [18]. In addition, the sensitivity to $0\nu\beta\beta$ decay in experiments with ^{76}Ge (Hidelberg-Moscow [19] and IGEX [20]) was increased up to $\sim 10^{25}$ y.

Since 2002 the progress in double beta decay searches has been connected with the two best present experiments, NEMO-3 and CUORICINO (see Section 2).

2. Best present experiments

2.1. NEMO-3

This is a tracking experiment that, in contrast to experiments with ^{76}Ge , detects not only the total energy deposition, but also other parameters of the process, including the energy of the individual electrons, angle between them, and the coordinates of the event in the source plane. Since June of 2002, the NEMO-3 detector [21] has operated at the Frejus Underground Laboratory (France) located at a depth of 4800 m w.e. The detector has a cylindrical structure and consists of 20 identical sectors. A thin (about 30-60 mg/cm²) source containing double beta decaying nuclei and having a total area of 20 m² and a weight of up to 10 kg was placed in the detector. The energy of the electrons is measured by plastic scintillators (1940 individual counters), while the tracks are reconstructed on the basis of information obtained in the planes of Geiger cells (6180 cells) surrounding the source on both sides. In addition, there is a magnetic field of 25 G parallel to the detector axis which is created by a solenoid surrounding the detector.

At the present time, studies are being performed on seven double beta decay isotopes; these are ^{100}Mo (6.9 kg), ^{82}Se (0.93 kg), ^{116}Cd (0.4 kg), ^{150}Nd (37 g), ^{96}Zr (9.4 g), ^{130}Te (0.45 kg),

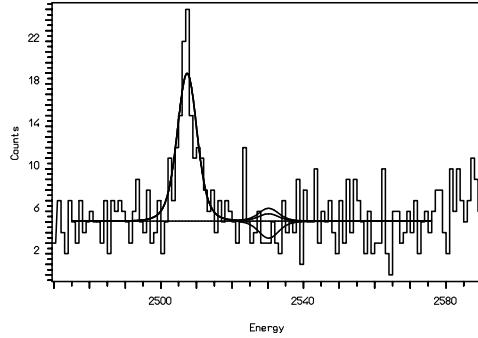


Figure 2. The sum spectra of all $^{nat}\text{TeO}_2$ crystals in the region of the $2\beta(0\nu)$ energy of ^{130}Te [23].

and ^{48}Ca (7 g).

Fig. 1 displays the spectrum of $2\beta(2\nu)$ events in ^{100}Mo that were collected over 389 days [22]. The total number of events is about 219,000, which is much greater than the total statistics of all of the preceding experiments. Given the calculated values for the detection efficiencies for $2\beta(2\nu)$ events, the following half-life value was obtained for ^{100}Mo :

$$T_{1/2}(^{100}\text{Mo}; 2\nu) = [7.11 \pm 0.02(stat) \pm 0.54(syst)] \cdot 10^{18} \text{ y} \quad (4)$$

Using 690 days of data the following limits on neutrinoless double beta decay of ^{100}Mo and ^{82}Se (mass mechanism; 90% C.L.) have been obtained: $> 5.8 \cdot 10^{23} \text{ y}$ and $> 2.1 \cdot 10^{23} \text{ y}$.

The corresponding limits on $\langle m_\nu \rangle$ are presented in Table 2.

2.2. CUORICINO

This program is the first stage of the larger experiment CUORE. The experiment is running at the Gran Sasso Underground Laboratory. The detector consists of low-temperature devices based on $^{nat}\text{TeO}_2$ crystals. The detector consists of 62 individual crystals, their total mass being 40.7 kg. The energy resolution is $\sim 8 \text{ keV}$ (FWHM) at 2.6 MeV.

The experiment has been running since March of 2003. The summed spectra of all crystals in the region of the $2\beta(0\nu)$ energy is shown in Fig. 2. The total exposure is $8.3 \text{ kg} \cdot \text{y}$ (^{130}Te). The background at the energy of the $2\beta(0\nu)$ decay is $0.18 \text{ keV}^{-1} \cdot \text{kg}^{-1} \cdot \text{y}^{-1}$. No peak is evident and the limit is $T_{1/2} > 2.4 \cdot 10^{24} \text{ y}$ (90% CL) [23]. The corresponding limits on $\langle m_\nu \rangle$ are presented in Table 2.

3. Best achievements

3.1. Two neutrino double beta decay

As discussed above this decay was first recorded in 1950 in a geochemical experiment with ^{130}Te [8]. In 1967, it was also found for ^{82}Se [24]. Attempts to observe this decay in a direct measurement employing counters were unsuccessful for a long time. Only in 1987 could M. Moe, who used a time-projection chamber (TPC), observe $2\beta(2\nu)$ decay in ^{82}Se for the first time [14]. Within the next few years, experiments employing counters were able to detect $2\beta(2\nu)$ decay in many nuclei. In ^{100}Mo [18, 25, 26], and ^{150}Nd [27] $2\beta(2\nu)$ decay to the 0^+ excited state of the daughter nucleus was also recorded. The $2\beta(2\nu)$ decay of ^{238}U was detected in a radiochemical experiment [28], and in a geochemical experiment for the first time the ECEC process was detected in ^{130}Ba [29]. Table 1 displays the present-day averaged and recommended values of $T_{1/2}(2\nu)$ from [30].

Table 1. Average and recommended $T_{1/2}(2\nu)$ values (from [30]).

Isotope	$T_{1/2}(2\nu)$
^{48}Ca	$4.2^{+2.1}_{-1.0} \cdot 10^{19}$
^{76}Ge	$(1.5 \pm 0.1) \cdot 10^{21}$
^{82}Se	$(0.92 \pm 0.07) \cdot 10^{20}$
^{96}Zr	$(2.0 \pm 0.3) \cdot 10^{19}$
^{100}Mo	$(7.1 \pm 0.4) \cdot 10^{18}$
$^{100}\text{Mo}-^{100}\text{Ru}(0_1^+)$	$(6.8 \pm 1.2) \cdot 10^{20}$
^{116}Cd	$(3.0 \pm 0.2) \cdot 10^{19}$
^{128}Te	$(2.5 \pm 0.3) \cdot 10^{24}$
^{130}Te	$(0.9 \pm 0.1) \cdot 10^{21}$
^{150}Nd	$(7.8 \pm 0.7) \cdot 10^{18}$
$^{150}\text{Nd}-^{150}\text{Sm}(0_1^+)$	$1.4^{+0.5}_{-0.4} \cdot 10^{20}$
^{238}U	$(2.0 \pm 0.6) \cdot 10^{21}$
$^{130}\text{Ba}; \text{ECEC}(2\nu)$	$(2.2 \pm 0.5) \cdot 10^{21}$

3.2. Neutrinoless double beta decay

In contrast to two-neutrino decay, neutrinoless double-beta decay has not yet been observed ¹.

The present-day constraints on the existence of $2\beta(0\nu)$ decay are presented in table 2. In calculating constraints on $\langle m_\nu \rangle$, the nuclear matrix elements from [34, 35, 36] were used (3-d column). In column four, limits on $\langle m_\nu \rangle$ are given, which were obtained using the NMEs (QRPA and RQRPA calculations) from a recent paper [37]. In this paper g_{pp} values (g_{pp} is a parameter in QRPA theory) were fixed using experimental half-life values for 2ν decay and then NME(0ν) were calculated. The authors [37] analyzed the results of all existing QRPA calculations which demonstrates that their approach gives the most accurate and reliable values for NMEs. There is criticism to this claim in [40]).

3.3. Neutrinoless double beta decay with Majoron emission

Table 3 displays the best present-day constraints for an ordinary Majoron (spectral index $n = 1$). For nonstandard models of the Majoron ($n = 2, 3$ and 7) the strongest limits were obtained with the NEMO-3 detector [41].

3.4. Improvements in experimental methods

The dominate experimental achievements are connected with the following methods:

- 1) Low background HPGe detectors made of enriched Ge (HM [19] and IGEX [20]).
- 2) Low background low temperature detectors (TeO₂ crystals; CUORICINO [22]).
- 3) Low background crystal scintillators ($^{116}\text{CdWO}_4$; SOLOTVINO [39]).
- 4) Low background tracking detectors (TPC [45], NEMO-3 [22]).

The key point is the level of the background, because high sensitivity experiments can only operate under low background conditions. The important achievements were done during the

¹ A fraction of the Heidelberg-Moscow Collaboration published a "positive" result for ^{76}Ge , $T_{1/2} \approx 1.2 \cdot 10^{25}$ y [31] (see table 2). The Moscow portion of the Collaboration does not agree with this conclusion [32] and there is independent criticism of this result (see, for example [33]). Thus at the present time this "positive" result is not accepted by the " 2β decay community" and it has to be checked by new experiments.

Table 2. Best present results on $2\beta(0\nu)$ decay (limits at 90% C.L.). *) See text.

Isotope	$T_{1/2}$, y	$\langle m_\nu \rangle$, eV [34, 35, 36]	$\langle m_\nu \rangle$, eV [37]	Experiment
^{76}Ge	$> 1.9 \cdot 10^{25}$	$< 0.33 - 0.84$	$< 0.46 - 0.59$	HM [19]
	$\simeq 1.2 \cdot 10^{25} (?)^*$	$\simeq 0.5 - 1.3 (?)^*$	$\simeq 0.6 - 0.7 (?)^*$	Part of HM [31]
	$> 1.6 \cdot 10^{25}$	$< 0.36 - 0.92$	$< 0.51 - 0.64$	IGEX [20]
^{130}Te	$> 2.4 \cdot 10^{24}$	$< 0.4 - 0.8$	$< 0.7 - 1.3$	CUORICINO [23]
^{100}Mo	$> 5.8 \cdot 10^{23}$	$< 0.6 - 0.9$	$< 2.0 - 2.7$	NEMO- 3 (this work)
^{136}Xe	$> 4.5 \cdot 10^{23}$	$< 0.8 - 4.7$	$< 2.8 - 5.6$	DAMA [38]
^{82}Se	$> 2.1 \cdot 10^{23}$	$< 1.2 - 2.5$	$< 2.3 - 3.2$	NEMO-3 (this work)
^{116}Cd	$> 1.7 \cdot 10^{23}$	$< 1.4 - 2.5$	$< 2.9 - 4.3$	SOLOTVINO [39]

Table 3. Best present limits on $2\beta(0\nu\chi^0)$ decay (ordinary Majoron) at 90% C.L.

Isotope	$T_{1/2}$, y	$\langle g_{ee} \rangle$, [34, 35, 36]	$\langle g_{ee} \rangle$, [37]
^{76}Ge	$> 6.4 \cdot 10^{22}$ [19]	$< (1.2 - 3.0) \cdot 10^{-4}$	$< (1.9 - 2.3) \cdot 10^{-4}$
^{82}Se	$> 1.5 \cdot 10^{22}$ [41]	$< (0.66 - 1.4) \cdot 10^{-4}$	$< (1.3 - 1.8) \cdot 10^{-4}$
^{100}Mo	$> 2.7 \cdot 10^{22}$ [41]	$< (0.4 - 0.7) \cdot 10^{-4}$	$< (1.3 - 1.8) \cdot 10^{-4}$
^{116}Cd	$> 8 \cdot 10^{21}$ [39]	$< (1.0 - 2.0) \cdot 10^{-4}$	$< (2.3 - 3.5) \cdot 10^{-4}$
^{128}Te	$> 2 \cdot 10^{24}$ (geochem)[42]	$< (0.7 - 1.6) \cdot 10^{-4}$	$< (1.7 - 2.8) \cdot 10^{-4}$

period of 2β -decay searches. In table 4 one can find the best background levels reached which were obtained in the different experiments. In 2-nd column, is the background B in $(\text{keV} \cdot \text{kg} \cdot \text{y})^{-1}$. For a better comparison of the experiments with different energy resolutions and efficiencies, a so called effective background value $\langle B \rangle$ has been introduced.

Table 4. Lowest levels of background in double beta decay experiments. ΔE is energy resolution (FWHM) in keV and η is efficiency; PSD is pulse shape discrimination.

Experiment	B , $(\text{keV} \cdot \text{kg} \cdot \text{y})^{-1}$	$\langle B \rangle = B \cdot \Delta E / \eta$, $(\text{kg} \cdot \text{y})^{-1}$
HM [19], IGEX [20]; ^{76}Ge	~ 0.2 $\sim 0.06(PSD)$	~ 0.8 $\sim 0.25(PSD)$
CUORICINO [44]; TeO_2	~ 0.18	~ 1.4
NEMO-3 [22]; ^{100}Mo	~ 0.001	~ 2.5
SOLOTVINO [39]; $^{116}\text{CdWO}_4$	~ 0.037	~ 10
TPC [45]; ^{136}Xe	~ 0.02	~ 15
DAMA [38]; ^{136}Xe	~ 0.06	~ 30

4. Conclusion

The principle achievements of past and present experiments are the following:

- 1) A conservative limit on the effective Majorana neutrino mass has been established as < 0.9 eV (90% C.L.).
- 2) A conservative limit on the coupling constant of Majoron to neutrino (ordinary Majoron) has been established as $< 1.8 \cdot 10^{-4}$ (90% C.L.).
- 3) The two neutrino double beta decay has been detected in 10 nuclei. In addition this type of decay to the 0^+ excited state of daughter nuclei has been detected (for ^{100}Mo and ^{150}Nd). Finally, the ECEC(2ν) process has been detected in geochemical experiment.

5. References

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